hydrogen too strong for enjoyment; therefore, as a health resort many parts of the coast might be advantageously exploited. To bathe in the warm waters of the Callirrhoe and then swim out upon the surface of the Sea and float lightly on those waters is an experience most pleasant.

In conclusion, I can but repeat what I have said elsewhere. "The Dead Sea is no respecter of persons, and has served all explorers alike. It is as strange and mysterious as ever. Mr. Gray Hill warns against all attempts to venture out upon it unless one has a staunch vessel. I repeat the warning. The Sea may appear fair and inviting to the tourist who lingers but a few minutes on the north shore; but, beware!"

THE DEVELOPMENT OF CUT-OFF MEANDERS.

BY

W. S. TOWER.

Purpose.—The following article represents a part of a year's work in physiography under the direction of Professor W. M. Davis, to whom the author owes much for helpful suggestions and criticism.

The object of the article is to describe and explain, as completely as possible, the essential features of successive stages in the development of a cut-off meander. In the course of the work both inductive and deductive methods have been found useful.

The order of procedure has been, first, to deduce the normal order of river changes in an ideal case. Then these expected changes have been confronted with the facts of observation. The two methods of investigation have been necessarily more or less concomitant. A systematic study of the Preliminary Maps of the Mississippi River and the Annual Reports of the Mississippi River Commission from 1880 to 1902 has been the main source of observed facts.

Definitions.—The definition of certain terms is made necessary by the general lack of satisfactory definitions both in text-books and in books of reference. Hence, to insure a clear understanding of their subsequent use, they are here given at the outset.

Meandering, a characteristic habit of mature rivers, may be defined as winding freely on a broad flood-plain, in rather regular river-developed curves. Under special conditions meanders may occur on plains not essentially river-made—that is, not flood-plains or incised below their original level.

A meander, a characteristic feature of a river that has reached maturity, is one of a series of regular curves, alternating right and

left along the river course. In Fig. 1 the curves A, B, D represent a series of meanders, free from many of the accidental irregularities of actual cases. Such curves are developed and controlled by the normal river process of cutting on the outer and down-valley bank and filling on the inner and up-valley bank of every turn. Each meander curve encloses a piece of land which may be called the lobe, L, L. These lobes are usually joined to the mainland by a narrow strip or neck, N, N. As its development progresses, the meander gradually enlarges, first the arc, and later the radius of curvature, and slowly advances down valley. From maturity of the river to old age, however, the meanders of any given part of the course are of successively different qualities; for, as the river grows older, it develops meanders of smaller radius and larger arc. At the same time the rate of down-valley migration of the meanders steadily diminishes. When, in this migration and enlargement two curves coalesce, a cut-off occurs, Fig. 1, H.

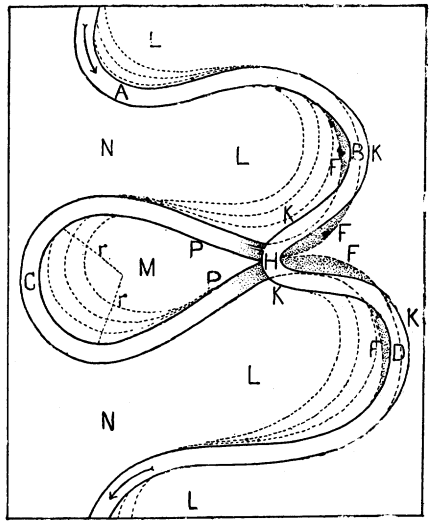

FIG. 1.
RIVER MEANDERS: YOUNG STAGE OF CUT-OFF.

Incised meanders.—The course of a river normally developed to maturity on a flood-plain may, by virtue of relative uplift of the land, be cut down below its original level and flow in a narrow valley. In this case the river meanders are said to be entrenched or incised. During the process of entrenchment, and before the river has again reached grade, the lateral cutting gives rise to steep slopes on the outer and down-valley sides of the curves, where the current is undercutting; and long, gentle slopes on the inner and up-valley sides of the curves, where the river is sliding off or withdrawing. At the same time the size of the meanders and the width of the meander belt are increased. When the river again reaches grade the development of the meanders follows essentially the same rules as before uplift occurred. The arm of the upland, now enclosed by each meander, may be called a spur, not a lobe. It is like the lobe

usually connected with the upland by a narrow neck. Incised meanders, however, are dependent for their occurrence on two cycles, and are not further considered in this article.

From this general definition a short definition may be evolved, by pruning and condensing, as follows: A meander is one of a series of regular curves, alternating right and left, developed by a mature river. In successive stages of development each meander enlarges and advances down stream.

The *radius* of curvature is the average of all the radii of the meander curve; in Fig. 1, r, r represent separate radii.

The *arc* of curvature is the length of the meander curve measured in degrees, Fig. 1, P, P.

A *cut-off* is the shorter path which a river follows in virtue of having cut through the neck of a lobe or spur, Fig. 1, H.

The *thread* of the fastest-flowing current is the locus of the fastest-flowing particles, and does not necessarily represent the continuous path followed by a single water particle.

The meander *belt* is the area enclosed between tangents to the outer curves on both sides of the stream.

Growth of meanders.—As a preliminary step to the consideration of cut-offs, let us see how the changes and growth of a meander are brought about. The general laws governing the formation of river meanders have been stated as follows:*

> The most important process in the development of river meanders is the displacement of the line of fastest current by inertia from mid-channel toward the outside of every curve. As a result, erosion tends to take place on the outside, and deposition on the inside of every curve. However slight the initial bends they will be increased, and as the valley floor is broadened the curves will be developed into systematic meanders of increasing radius and breadth . . . A river not only tends to increase its meanders; it also tends to push the whole meander system down the valley. This is because the line of fastest current, displaced towards the outside of every curve, enters the succeeding curve (or stretch between two curves) near the down-valley bank, which is therefore worn away, while the opposite up-valley bank is built out.

Effect of Gradient.—The amount of displacement of the thread of fastest current which controls lateral erosion is determined by (1) the strength of curvature of the turn, and (2) the mass and velocity of the river. Cutting and filling of the banks should be equal in amount, and should vary directly with the amount of displacement, though not necessarily in the same ratio. Other things being equal, then, a steeper, and hence swifter, river should show the

* Prof. W. M. Davis; River Meanders, p. 146, Geol. Mag., Dec. IV, Vol. X, 1903, 145–148.

most lateral cutting and the greatest development of meanders. But that is not the case. Not only the fact of cutting, but also the place of cutting, must be considered. The greater the velocity of a river, the longer will it take for any curve to cause maximum displacement of the current and the farther down stream from the beginning of the curve will maximum cutting occur. Hence, the curves of a stream on a steep gradient will enlarge slowly, but will rapidly advance down valley (Fig. 2, curve A). The curves of a less rapid stream will enlarge steadily, and slowly move down valley, Fig 2, curve B. In any given stream, then, the gentle turns and bends along the steeper initial course will, without much change of character, progress rapidly down valley. On the gentler slopes of the later stages, curves of more and more symmetrical form will be developed and their down-valley migration will diminish. A river of great extent may show, in different parts of its course, all phases of meander growth at the same time. In the well-graded lower courses the best-developed meanders would be expected, with a gradual transition toward the head-waters to the simpler conditions of youth.

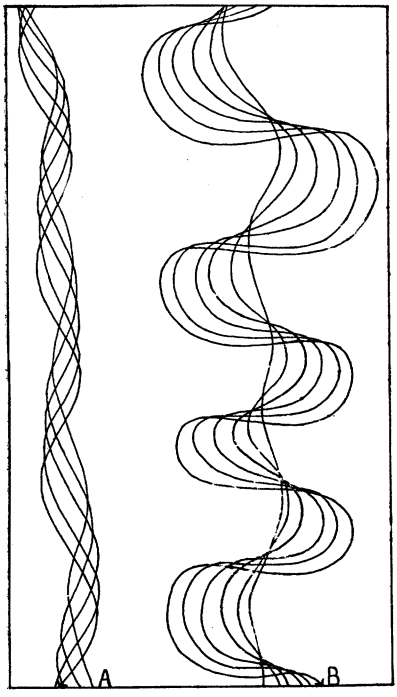

FIG. 2.
DEVELOPMENT OF MEANDERS IN RIVERS OF STEEP AND OF GENTLE GRADIENTS.

Formation of a Cut-off.—The growth of a single meander on a mature river includes all the stages from an initial bend to the closed curve of the mature river. The first visible change expected is an increase in the arc of curvature, followed by a lengthening of the radius. When the continued action of enlargement and down-valley migration causes two curves to coalesce a cut-off occurs.

Changes following a Cut-off—Rapids.—The first result of a cut-off will be to afford the river a new, shorter course, in which the gradient is much steeper than elsewhere. This will cause at least a part of the stream to turn through the new course and form rapids.

Its ability to maintain a graded course, however, enables the river to distribute the steeper slope up and down stream, and the rapids will quickly disappear.

Change of Current.—The position of the fastest-flowing current, previous to cut-off, is near the outer bank of the curve on both sides of the neck. When the neck is cut through, the movement of part of the current through the cut-off must shift these positions. Following the steeper slope, the current on the up-valley side of the neck must turn more and more through the cut-off, enlarging the breach, and more or less completely abandoning its former course round the meander curve. At the same time, the entrance of the cross-current will crowd away the current on the down-valley side of the neck from its former position, forcing it toward the lobe of the next down-stream meander.

Change of Banks.—Any change in the position of the current destroys the previous condition of balance between current and bank. Changes in the banks must therefore result; places where cutting was formerly going on may now be filling; and banks recently built may now be eaten away. The crowding of the current toward the down-stream lobe causes erosion of the bank. The place where such erosion occurs may be called a *nip*. Fig. 1 shows an early stage in which a cut-off has occurred, at H, with the formation of nips at K K, the dotted line indicating the former position of the bank. The withdrawal of the current from the outer side of the curve leaves that bank bordered by quiet water, in which deposition will probably result. Such deposition may be called a *fill*, Fig. 1, F F. Fills may or may not be continuous with the former banks; for the sudden change of the current may, on the first fill down valley from the neck, cause deposition away from the bank, and separated from it by a narrow strip of water or slough.

During these changes in current and banks down stream from the cut-off similar changes will occur up stream. By virtue of the rush of a current through the cut-off, water is drawn from the neighbouring up-stream parts of the river. To supply the current caused by this withdrawal, there is a rapid inflow from adjoining parts of the stream, which tends to shift the line of fastest current away from the outer bank. The changes due to this shifting are similar to the changes below the neck. Here, as there, nips are formed where deposition was formerly going on, and fills are made where active cutting occurred before.

Arrangement of Nips and Fills.—A new series of lateral swings

of the current is soon developed, and, from their extension and continued action, a systematic pattern of nips and fills should result. Nips and fills should occur both up stream and down stream from the cut-off—possibly more evident down stream than up stream—alternating from side to side along the river's course. The initial fills form on either side of the cut-off neck; the initial nips opposite them. Other nips and fills of rapidly-decreasing strength should occur indefinitely up and down the stream.

New Meander.—In the course of these changes all the flow of water round the old meander will cease. It then becomes a dead-water area. The ends of the deserted curve favour the deposition of silt, and soon fill up, and an "ox-bow lake" results. In a late stage after cut-off, the river will reach the conditions shown in Fig. 3. The nips, K K, and fills, F F, increase in size and extent farther up and down stream, while the original swing of the current round the remnant of the cut-off neck results in the birth of a new meander, A, somewhat down stream from the cut-off.

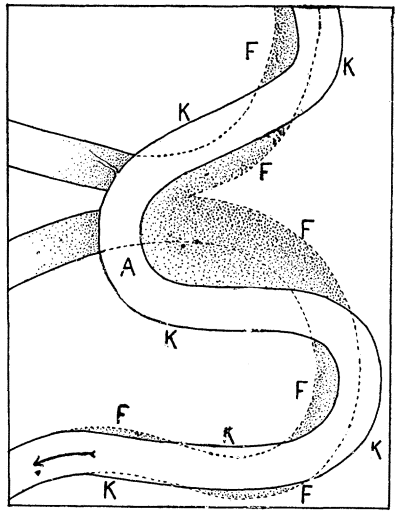

Fig. 3.
LATE STAGE AFTER CUT-OFF.

Summary.—Briefly, then, the expected results of a cut-off are certain definite changes in the position of the current both above and below the neck. These changes of current are accompanied by the development of a systematic pattern of nips and fills, and eventually by the formation of a new meander.

Facts of Observation.—Though inductive and deductive methods of reasoning were carried on together, the inductive consideration has, for convenience of presentation, been placed here after the purely deductive side. The main source of observed facts has been from a study of the Preliminary Maps of the Mississippi River—thirty-two in number—which cover the river from Cairo, Illinois, to the Gulf. The surveys of 1883, in black, and the re-surveys of 1895–96 in red overprint, afford an excellent opportunity to study river changes from careful records. The discussion of the facts of occurrence, the conclusions to be drawn from them,

and a comparison with deduced results form the latter part of the article.

Deflection of Current.—The position of the thread of fastest current is not shown on the maps. The location of the main channel is given, however, and, indicating greatest depth, has been considered as indicating the position of the fastest current. In every case the main channel, and hence the current, shows the well-known displacement toward the outer bank of the curve; its closeness to the bank depending upon the strength of curvature of the particular turn. On some of the most perfect meanders, as on Rowdy Bend, above Greenville, Miss., maximum displacement brings the channel within a few hundred feet of the bank, or about one-eighth of the width of the stream at that point.

Cutting and Filling.—Displacement of the current has caused in every case some erosion of the banks where they are unprotected by revetments. Perhaps the most striking example of this is seen at Raleigh Landing, about fifteen miles above Vicksburg, Miss., which in twelve years was forced back over a mile. Less marked examples occur at many other points along the river, among which may be mentioned Rivers, Avalanche, Lee's and Ship Bayou landings, near Natchez, Miss., all of which were moved back half a mile or more. As was expected, the erosion of one bank is accompanied by filling along the other, so that the width of the river remains fairly constant. Out of the twenty cases in which a marked amount of both cutting and filling was measured, more than half showed the two processes to be practically equal in effect. In a few cases the amount of filling fell below the amount of cutting. For the most part, however, where the two processes differed at all, the amount of filling was greater than the amount of cutting. In looking for an explanation of this unexpected condition, it appeared from the maps that the greatest excess of filling over cutting occurred on bends of strong curvature. Furthermore, in many of the best-developed meanders, as at Greenville, Miss., above Arkansas City, Ark., and again at Raleigh Landing, there is a fairly distinct excess of filling on the outer or stronger part of the curve. It seems probable that the stronger the curve, the greater the displacement of the current, the more sluggish the water along the inner bank, and the greater the amount of deposition—even to an actual narrowing of the stream. Conversely, we ought to expect the river to be the widest in the reaches and on the gentle curves—a condition which, though modified in many cases by local conditions, holds true in general.

Rate of Cutting.—The rate of lateral cutting depends on the amount of deflection, as shown by comparing a strong and a gentle curve. Two such curves are shown just below Natchez, Miss., at Esperance Point, and at Dead Man's Bend. Both have about the same arc of curvature. The former has a radius of less than one and one-half miles; the latter is much longer, and has a radius more than twice as great. The first, therefore, is much the stronger curve, and shows a maximum cutting of over half a mile; while the second shows hardly more than one-eighth of a mile in the interval of twelve years between the surveys.

Down-Valley Migration.—In passing from one curve to another of reversed direction, the current, as indicated by the position of the channel, is seen to enter the second curve flowing nearer the inner or the down-valley bank. In many cases this has resulted in giving the maximum amount of cutting on the down-valley bank, which, together with the filling on the opposite bank, causes a distinct movement of every meander down valley. On all of the curves, as at Raleigh Landing, at Esperance Point, Louisiana Bend, etc., the down-valley migration is shown to a greater or less degree. The amount of migration, however, seems to vary. In general, it may be said, that in early stages of meander growth there appears to be a more rapid down-valley migration, and that with an increasing arc of curvature migration decreases.

Thus, the observed facts bear out all the deduced conditions of river change previous to cut-off. It remains only to test in the same way the expected conditions subsequent to cut-off.

Changes Subsequent to Cut-off.—Following the general laws of river action, certain results were expected from the formation of a cut-off—namely, the existence of temporary rapids; the displacement of the fastest-flowing current on both sides of the cut-off, destroying the condition of equilibrium between current and bank; the development of a systematic pattern of nips and fills; and, finally, the growth of a new meander a little way down stream from the older one.

Rapids and Changes of Current.—Some of these deduced results, such as the existence of rapids, cannot be proved from the study of maps, but their occurrence has been noted by observers near at hand at the actual moment of cut-off. Furthermore, the maps show numerous examples of different stages in the shifting of the current after cut-off; but, for the most part, they are rather late stages, and do not give the early changes of the current. It is not unreasonable to suppose, however, that the later stages shown on

the maps, and which fall into the deduced scheme, are reached, not suddenly, but by a series of systematic stages, each of which will itself fall into the scheme.

Nips and Fills.—The conditions at Davis's cut-off, just south of Vicksburg, Miss.—sheet 18—show a rather advanced stage after cut-off, which suffices to show how closely the actual resembles the late stage of the ideal case, as shown in Fig. 3. The principal difference is that the initial nip and its associated fill up stream from the cut-off have been obliterated by the normal down-stream migration of the river curves. A much earlier stage is shown by the comparatively recent cut-off at Coles Point,* where a condition closely analogous to Fig. 1 is shown. It also shows the down-stream fill from the cut-off as a distinct island, with a slough behind it, indicating a rapid change in position of the current.

Arrangement of Nips and Fills.—At Davis's cut-off the alternating arrangement of nips and fills, both up and down stream from the cut-off, is apparent, with some indication, also, that the nips are larger down stream than up stream. In both directions from the cut-off the size of the nips and fills rapidly diminishes. For example, the first down-stream fill shows a maximum width of over 2½ miles, the second is less than one-third that width, and the third is still smaller, beyond which they rapidly diminish until they quickly cease to appear. Theoretically they should extend, with decreasing effect, indefinitely in both directions. In the actual cases the decrease is so rapid that it soon becomes impossible to draw any line between the special effects due to cut-off and the normal action of the river.

Number of Nips and Fills.—A count of the nips and fills associated with fifteen cut-offs showed them in every case to be equal in number; that is, for every nip there was an associated fill. Up stream from the cut-off the minimum number of nips and fills was 1 of each, the maximum number 3, with an average in the fifteen cases between 1 and 2. Down stream from the cut-off the minimum was again 1, the maximum 5, with an average of 3. The figures in each case apply only to those changes in the banks which were distinctly due to cut-off.

Formation of New Meander.—In early stages after cut-off the river-ends of the old meander become silted up, with the formation of a so-called "ox-bow" lake. One of the largest cut-off meanders is the one already mentioned at Davis's cut-off, Palmyra

* See Fig. 7 in an essay by R. M. Brown, "Mississippi River from Cape Girardeau to the Head of the Passes," Bull. Am. Geog. Soc., Dec. 1903. Vol.

Lake; other examples may be seen at many points along the course of the river. At the same time with the silting up the acute end of the neck of the lobe may be nipped and blunted by the outward cutting of the current. In most cases, however, this outward cutting does not proceed precisely in the direction of the former meander, for the habit of all curves to move down valley gradually carries the new curve away from the immediate vicinity of the cut-off lobe. This is particularly well shown at Davis's cut-off, where a well-developed curve already exists. With but a single exception, every case so far observed shows the formation of a new meander in some stage of development down valley from the cut-off.

It has been reported recently that the down-valley migration of the curve above Sargent's Point, below Vicksburg, has allowed the river to cut through the neck and return to its former course, long known as Lake Palmyra. By this change several cotton plantations were practically ruined, Davis Island was restored to the Mississippi mainland, and further growth of the meander below Davis's cut-off was probably stopped.

Application to Mexican Boundary Question.—The importance of clearly recognizing these processes of river change in meander growth and in the formation of cut-offs is shown by the recent report on the "Proceedings of the International (water) Boundary Commission United States–Mexico" [Washington, 1903, 2 vols.]. In 1852 a treaty between the two countries placed the boundary in the middle of the channel of the Rio Grande River, which, below Rio Grande City, meanders very freely, and also, during flood-time, often changes its course abruptly. To avoid complications that might arise from such changes in the channel, it was stipulated that the boundary should continue to follow the channel of the river, provided that alterations in the course "be affected by natural causes through the slow and gradual erosion and deposit of alluvium." In all other changes, sudden or artificial, the boundary should follow the original channel at the time of making the treaty. According to the treaty, normal cutting and filling on meander curves was interpreted, no matter how great in amount, to be a slow and gradual change. The boundary, therefore, migrated with the river, and what one State lost by erosion was added to the other by filling. For example, nearly half the city of El Paso is located on land built by the river and added to Texas since 1850.

Cut-offs, on the other hand, the ultimate result of "slow and gradual erosion," were considered to be sudden or "avulsive"

changes, the results of caprice on the part of the river, and, therefore, the boundary remained in the middle of the former channel.

It is estimated that fifty cut-offs have occurred since the treaty was made, leaving the cut-off lobes, or *bancos*, as they are locally known, on the opposite side of the river from the country to which they belong. In some cases the bancos are left entirely shut off from the river and surrounded by domain and people under a different Government. Under these conditions, to quote from the U. S. Commissioner,

> it will be easy to see that the laws, local, state, and federal, will be administered only under great difficulty. The products of the bancos could not be sold to citizens of the country in which the banco is located without violating the revenue laws, nor transported for sale to the country to which the banco belongs without violating similar laws. The violators of the laws of the country to which the banco belongs could not be arrested and conveyed to the country having jurisdiction without special extradition laws.

In 1893 a dispute arose over the Banco de Vela. Citizens of both countries were arrested and imprisoned; troops were sent to the vicinity, and both countries threatened to seize the island. A joint commission was appointed to settle the questions in dispute. As the simplest remedy for the difficulties, the Commission suggests that a banco be no longer considered as due to "avulsive" change, and that arrangements be made for the transfer of jurisdiction to the country in which it is located, provision being made for the transfer of titles to land and for the inhabitants, if there be any, to retain their former citizenship if they choose.

Summary.—From the foregoing discussion and illustrations it appears that the development of river meanders is an endless sequence, the importance of which must be recognized in making any river the boundary of a State or country. From initial bends and turns the river produces, by constant, well-defined processes, a systematic pattern of meanders. The meanders in their development pass through a series of stages which follow a regular scheme except as interrupted in times of flood by sudden changes known as short-cuts. The final stage of the growth of a meander, the stage of cut-off, leaves the river with a new bend, from which the process may be repeated. There may, therefore, be in one part of a mature river all stages of meander growth at one time.